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Performance evaluation of a software engineering tool for automated design of cooling systems in injection moulding

Juan M. Jauregui-Becker^{a*}, Guido Tosello^b, Fred J.A.M. van Houten^a, Hans N. Hansen^b^a University of Twente, Laboratory of Design, Production and Management, P.O. Box 217, 7500 AE Enschede, The Netherlands^b Technical University of Denmark (DTU), Department of Mechanical Engineering, Produktionstorvet 427A, DK-2800 Kgs. Lyngby, Denmark* Corresponding author. Tel.: +31-53-4892266; fax: +31-53-489-3631. E-mail address: j.m.jaureguibecker@utwente.nl

Abstract

This paper presents a software tool for automating the design of cooling systems for injection moulding and a validation of its performance. Cooling system designs were automatically generated by the proposed software tool and by applying a best practice tool engineering design approach. The two different design methods (i.e. automatic and manual) were applied to the mould design of two thin-walled products, namely a rectangular flat box and a cylindrical container with a flat base. Injection moulding process simulations based on the finite element method were performed to assess the quality of the moulded parts. Results indicate the tool is capable of generating feasible cooling solutions. Recommendations are provided for improving the performance of the tool.

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Keywords: Automatic design; injection moulding; cooling system; simulation

1. Introduction

Currently, analysis tools capable of simulating the cooling phase of the injection moulding process are integrating optimization routines to minimize cooling time and obtain more homogeneous temperature distributions of the plastic part while cooling [1-3]. However, a human designer has to create the initial design first from where computer aided engineering and optimization methods can be applied. In fact, optimizing cooling channels placement and diameter results in local optimum, given that the initial design bounds the possibility of finding global optimal. Therefore, making a good initial design is of paramount importance. Furthermore, as conformal cooling is gaining popularity as a method to enhance injection moulded part quality and process efficiency and products are becoming more complex, the task of designing an effective cooling system is becoming increasingly difficult. Therefore, the availability of software tools to fully automate the design of cooling systems is of high industrial relevance. Although automating design problems has been extensively investigated over the past 30 years [4], not

much literature addresses the problem of automating injection moulding cooling design.

Recent research developed by Li et al. [5-7] has resulted in a method for automating the design of cooling circuits for injection moulding. The method consists of decomposing the part geometry into several predefined shapes. Then, three techniques are collaboratively used for candidate solution generation: (1) case-based design, (2) graph-based search and (3) heuristic search. Case-based design maps the shape features to predefined solutions, obtaining a preliminary design that is captured in a graph model. A graph based transversal algorithm is employed to search for candidate cooling circuits. Heuristic search develops the candidate solutions into layout designs that contemplate tentative manufacturing plans. Although this approach has demonstrated to be capable of automating the generation of cooling solutions, it suffers from the drawback that the design has a strong dependency on the accuracy of the shape recognition algorithm as well as on the quality of the sub-solution predefined for each shape feature. Furthermore, complex algorithms are required to solve geometric constraints and keep the physical consistency of the cooling solutions (e.g. make sure cooling channels are connected to form a circuit).

In this context, the present research introduces a method for automating the design of cooling systems in injection moulding. The method has been implemented into a software tool and a performance evaluation of the tool was performed. The method applied for automating the design of cooling system is based on three rationales. Firstly, cooling systems can be structured in different levels of information detail and their design can be done by incrementally taking independent design decisions at each of these levels. Secondly, cooling systems are composed out of different types of cooling channels, and each type of cooling channel fulfil a different sub-function in the system. Thirdly, by discretizing a CAD model of a mould into a 3 dimensional mesh of voxel elements, a logic representation of the geometry is obtained that enables human-like reasoning for design proposes. A complete description of these rationales has been described by the authors in [8].

Injection moulding process simulations based on the finite element method were performed to assess the quality of the moulded parts depending on the employed cooling system design. The cooling system design was automatically generated by the proposed software tool and by applying a best practice tool engineering design approach. The two different design methods (i.e. automatic and manual) were applied to the mould design of two thin-walled products, namely a rectangular flat box and a cylindrical container with a flat base. Different cooling systems produce different warpage conditions in the part and therefore different geometrical form error. The process simulation results in terms of part accuracy (e.g. form error such as flatness and roundness) obtained from both cooling systems designs were compared in order to actually evaluate the validity of the cooling design system proposed by the automatic solutions. The paper concludes that the tool is capable of generating feasible solutions. Recommendations are provided for improving the performance of the tool.

2. Automated cooling design method

This section describes the rationales of the automation method, its steps and implementation. As the goal of this paper is to present an overview of the method and some preliminary results on its performance, only a general description is provided.

2.1. Rationales

The cooling design automation method is based on three rationales, or principles.

Firstly, *cooling systems can be designed incrementally* according to the following structure:

- determining geometric points where cooling channels can be placed;

- joining points to create cooling channels;
- joining cooling channels to create cooling circuits;
- grouping cooling circuits to obtain cooling systems.

Secondly, *different type of cooling channels can be defined* by assessing the functions they fulfil in the systems. The analysis results in the identification of 3 types of channels: absorber channels, connector channels and exchange channels. Absorber channels fulfil the function of cooling the melt down. These are channels placed close to the part geometry and arranged such that heat is transferred in a homogenous manner from the melt to the coolant flowing through it. Connector channels fulfil the function of transporting the coolant between channels absorbing heat such that cooling circuits can be constituted in one of the mould parts. Exchange channels fulfil the function of exchanging coolant with the environment. This type of channels is placed at the surfaces of mould where the heat dissipation devices are connected to.

Thirdly, *voxels* (that are defined as 3D pixels) *type can be attributed depending on the component* type they are located at. By using voxels, the geometric model can be transformed into a logic one. Although this transformation results in a loss of geometric information, it also eases solving spatial constraints.

2.2. Method steps

The three principles presented in the previous section can be applied in a design automation method that consists of five steps, as indicated in Figure 1. The following subsections describe further these steps.

Step 1: Voxel mesh generation

The first step in this method consists of generating mesh of voxels superimposed on a CAD model of the mould. A ray tracing algorithm is employed for this purpose. Table 1 summarizes the attributes of a voxel depending on the component they are located at.

Table 1: List of attributes of a voxel element.

| Attributes | Description | Model |
|---------------|---|---------------|
| Core | Identifies the core of the mould | Boolean |
| Cavity | Identifies the cavity of the mould | Boolean |
| Product | Identifies the product or plastic part of the mould | Boolean |
| Inlet/outlet | Identifies if a surface is used for inlets or outlets | Boolean |
| Non Drillable | Identifies if a surfaces cannot be drilled | Boolean |
| Size | Defines the size of the vertices of the voxel | Double |
| Position | Defines the position of the voxel | Double[i,j,k] |

The size of the voxels is calculated such that the volume of plastic part is entirely traceable in the mesh. Figure 1(a) shows schematically the cavity and core of an example mould. Figure 1(b) shows how the voxel mesh is applied in that case.

Step 2: Points Generation

After making the voxel mesh, a 3D grid of points is generated and superimposed on voxel mesh model of the mould. This is schematically indicated in Figure 1(c). The distance between points in the grid is based on relation shown in [9], where empiric values for the distance between cooling channels and melt depending on the thickness of the plastic part being produced are presented. The objective of this step is to define the spatial locations in the mould where cooling channels can eventually be placed as well as those places where it cannot. To do so, a “colour” is attributed to each point in the grid, see Figure 1(d). This assigned attribute is used to characterize the function of the point. These are:

- Blue: defines points that can be used to create an Absorber channel.
- Green: defines points that can be used to create a Connector channels.
- Brown: defines points on the surface of a core and cavity where Exchanger channels can be placed.
- Grey points: defines points nearby the melt where channels cannot be placed to overcome mould break.
- Black points: defines points where channels cannot be placed to avoid mould break.

The colour of a point is determined as a function of the voxels surrounding that point. In Table 2 the logic relations to determine the colours are presented. Figure 1(e) shows how points are attributed with colours as a function of the voxels in their vicinity. This step determines the solution space of each design function in the problem, namely, to cool the plastic part (blue points), to transport the coolant (green points) and to exchange the coolant with exterior heat dissipation devices (brown points).

Table 2: Logical relations defining point's colours.

| Point Colour | Surrounded by |
|--------------|--|
| Green | core or cavity voxels |
| Brown | (core or cavity voxels) and exchanger voxels |
| Black | (core or cavity voxels) and (non-drillable voxels or product voxels) |
| Grey | (core or cavity voxels) and (product voxels) |
| Blue | (core or cavity voxels) and (Grey points) |

Step 3: Absorber Channels Generation

Once all the points have been generated, channels are placed close to the part geometry by connecting blue points. This step results in a large number of cooling

channels, which do not have to necessarily be used all together. Figure 1(f) indicates the result of applying this step.

Step 4: Circuits Generation

Cooling circuits are designed by identifying first absorber channels capable of forming a circuit, secondly connecting them by using connector channels to guarantee that coolant can flow, and lastly by connecting the resulting circuits to the surface of the mould using exchange channels. The layout of both connector channels and exchange channels is obtained by applying the A* algorithm [10] to search for feasible paths using green points for connector channels and brown points for exchange channels.

Step 5: Cooling Systems Generation

Cooling systems are generated by combining cooling circuits such that heat absorption and cooling homogeneity are maximized. In the implementation developed in this work, this is performed by randomly combining cooling circuits and these performances.

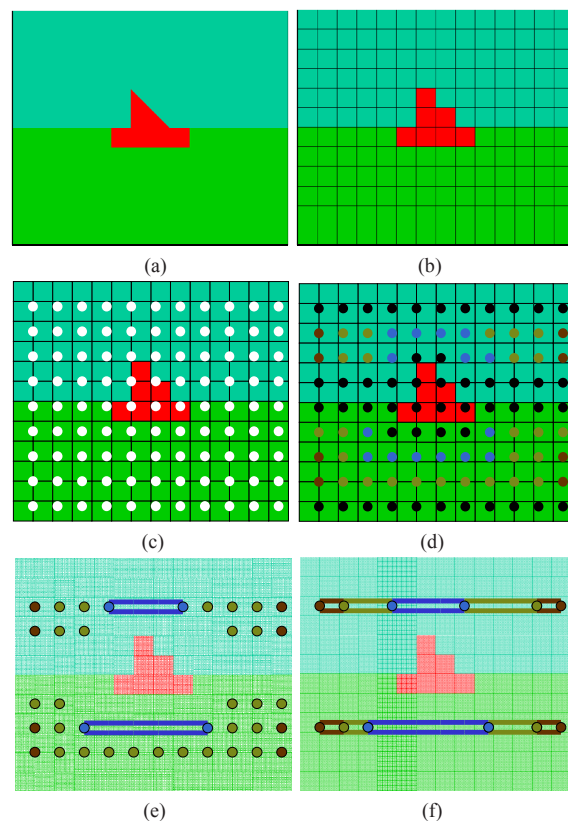


Figure 1: Schematics of the cooling design automation method: (a) the initial state of the mould; (b) voxel mesh of mould parts and plastic parts; (c) grid of points superimposed on voxel mesh; (d) points get a colour; (e) blue points are connected creating Absorber Channels; (f) connection channels and Exchanger form circuits.

2.3. Implementation

The method and algorithms for cooling generation have been implemented using C# [11]. SolidWorks® [12] is used as interface for modelling the 3D mould parts. Furthermore, a User Interface (UI) was developed using SolidWorks® API [12]. The result of applying this method is a large solution set of cooling systems that satisfies the constraints and goals of the design problem. The solution set can be assessed by using the solution space graph shown in Figure 2. Each point in this graph corresponds to one cooling system layout. Characteristic to the solution space explorer graph is that designers can plot the solution space for different properties of the cooling system, as for example its length, number of required drilled holes and temperature homogeneity index. By assessing several performances, designers can select a desired solution.

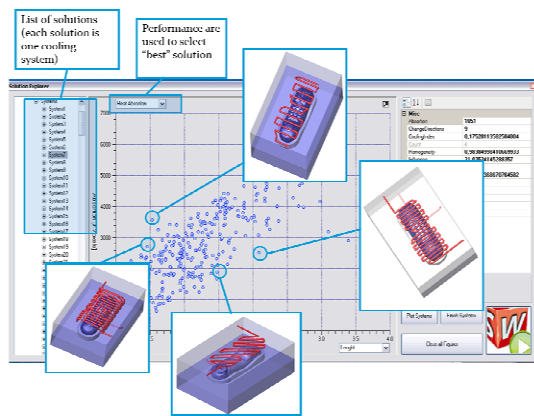


Figure 2: The solution explorer graph showing automatically designed cooling systems for a telephone mould.

3. Process simulation and product quality prediction

Process simulations in injection moulding are carried out with the multiple purposes of analysis and optimization of part, tool, and process designs. With injection moulding simulations it is possible, for example, to make changes to product design before first tooling trial, check part quality before production, reduce costly mould modifications, optimize tool design to increase part quality and productivity, reduce number of mould trials, establish acceptable processing window, or perform a careful injection moulding machine selection. In the present case, the goal of performing injection moulding process simulations was to predict the part quality depending on the different tool design (i.e. the two different cooling designs), given the following inputs:

- Product design – two product geometries were considered (cylindrical container and square box) (see Figure 3);

- Material selection – an ABS (Acrylonitrile Butadiene Styrene) amorphous copolymer Lustran ABS 488 by INEOS ABS was adopted in all studies (Figure 4);
- Injection moulding process – parameters were set according to the polymer material supplier and in order to be able to successfully complete the process in terms of complete part filling, packing and cooling (see Table 3);
- Injection moulding machine – a general purpose conventional injection moulding machine capable of providing the needed clamping force and injection flow rate was selected.

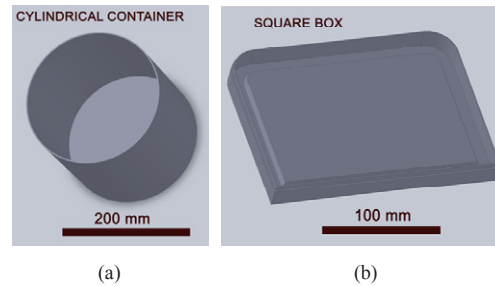


Figure 3. (a) Cylindrical container: diameter = 200 mm, height = 200 mm, part thickness = 2 mm; (b) square box: length = 200 mm, width = 150 mm, part thickness = 3 mm.

Table 3. Injection moulding parameters.

| Parameters | Cylindrical container | Square box |
|-------------------|-----------------------|------------|
| Melt temperature | 260 °C | 260 °C |
| Mould temperature | 80 °C | 80 °C |
| Injection speed | 50 mm/s | 50 mm/s |
| Packing time | 20 s | 15 s |
| Packing pressure | 50 MPa | 50 MPa |
| Cooling time | 10 s | 15 s |

An optimal cooling design allows for both an improved part quality by means of a uniform cooling (and therefore a reduced differential shrinkage, which guarantee low warpage) and also higher productivity due to a shorter cycle time because of reduced cooling time. To evaluate the performance of the cooling design software tool, the focus of the present investigation was to keep constant the injection moulding set-up in terms of filling, packing, and cooling parameters and to compare the output of the process simulations in terms of product quality (i.e. warpage).

Injection moulding simulations were performed using the commercially available Autodesk Moldflow Insight [1] software package using the generalized Hele-Shaw (GHS) flow model introduced by Hieber and Shen [13]. The GHS model is the most common approximation that provides simplified governing equations for non-isothermal, non-Newtonian and inelastic flows in a

three-dimensional geometry with a thin cavity thickness, meaning that the thickness in the direction perpendicular to the flow direction is considerably smaller (e.g. ratio $<1/10$) than the dimensions parallel and across to the flow direction. As a consequence, the assumptions of the GHS flow model are that the velocity component in the direction of thickness is neglected, inertia and gravitational forces are much smaller than viscous forces, the flow kinematics are shear-dominated and the shear viscosity is taken to be temperature and shear rate dependent (see Figure 4a). The thin-wall characteristic typical of the geometries considered in this study allowed to employ the GHS model, which permits fast and yet reliable simulations [14]. Therefore the parts' surfaces were meshed with a 2D triangular mesh, whereas the thickness was discretized using 12 laminate layers. The meshed components are depicted in Figure 5.

The warpage calculation starts after the packing phase, where the initial strains are taken from the pvT material properties calculated in its conditions at the end of packing (including the shrinkage variation due to material melt/solid state transition) (see Figure 4b).

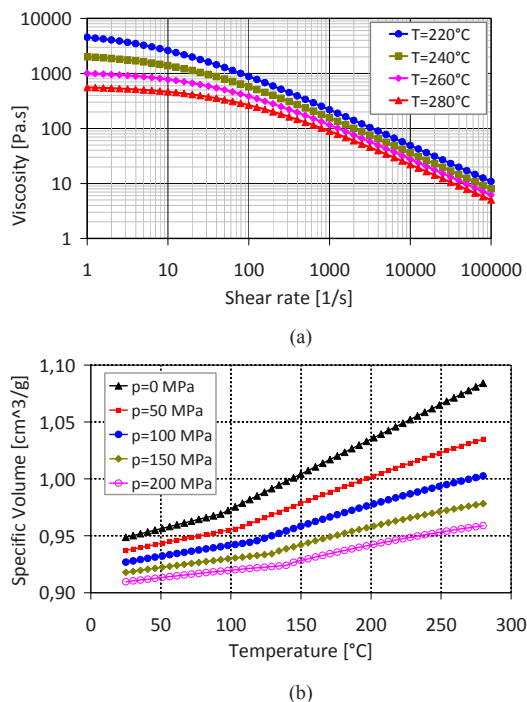


Figure 4. Material properties of Lustran ABS 488: (a) shear rate and temperature dependent viscosity; (b) pressure and temperature dependent specific volume (pvT diagram).

The relation between stress and strains are then calculated by including the thermal strain, with the use of coefficient of linear thermal expansion (CLTE) and the temperature. The initial stress induced by the flow is added to the stress. The mechanical properties used for

the calculation are obtained in this case from an isotropic model (i.e. equal material properties for both the flow and the transverse flow direction). The isotropic material properties are the Young's modulus, Poisson's ratio, and the CLTE. At the end of the packing phase the constraint of having the part in the mould is applied and the shrinkage, and hereby deformations, of the part are calculated from the CLTE, and this constraint is kept until the end of the cooling phase. Hereafter the deformation is free form and is only dependent on the temperature drop from the ejection temperature down to room temperature.

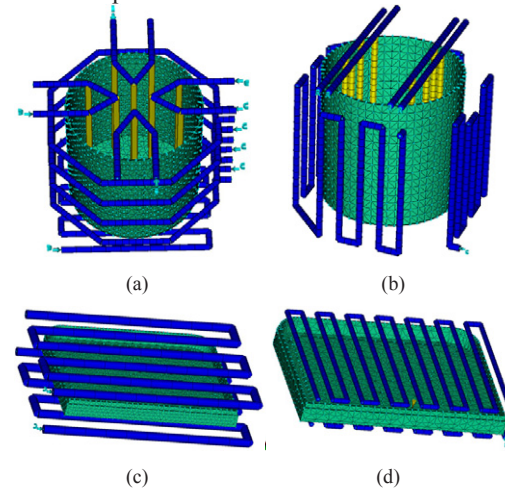


Figure 5. Meshed geometry of cylindrical container with cooling channel design by (a) tool engineer (ENG) and (b) Design Automation Software (DAS); meshed geometry of square box cooling with channel design by (c) tool engineer (ENG) and (d) DAS software.

The warpage analysis uses the filling results to consider the effect from the flow behaviour, then uses the packing results to consider the effect of the volumetric shrinkage and finally uses the cooling results to consider the effect of the thermal strain. As a result, it is possible to calculate the dimensional displacements of the mesh nodes from their initial position in the model as a result of the combined effects of filling, packing and cooling phases. The performance of the different cooling designs has been evaluated on the basis of the comparison of such displacements.

3.1. Cylindrical container

The effect of cooling design on warpage of the cylindrical container was evaluated in terms of: (a) flatness of the surface at the bottom of the product; (b) the roundness at the top of the product. The cooling design suggested by the DAS software exhibits two cooling channels less than the ENG design. As result, the flatness error at bottom of the cylinder is 0.25 mm with the DAS cooling design, and of 0.15 mm with the

ENG cooling design. Cooling channels around the lateral surface of the cylinder appear less evenly distributed in the DAS design than in the ENG design. Effect of this difference in the cooling design can be observed in the roundness of the top edge of the product (see Figure 6).

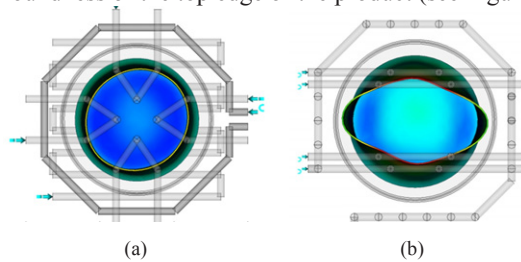


Figure 6. Comparison of product final shape (displacement magnification 50x) of part moulded with injection tool having (a) ENG design (roundness 0.2 mm) and (b) DAS design (roundness 1.5 mm).

3.2. Square box

The effect of cooling design on warpage of the square box was evaluated in terms of: (a) flatness of the bottom surface; (b) flatness of the lateral walls surface. The ENG cooling design and the DAS design give a similar deformation pattern of the box due to the similar cooling channel layout (see Figure 7). However, it appears from the analysis that the solution adopted by the DAS (i.e. a higher number of cooling channels with a smaller diameter) gives a better result on the flatness of the box. Results are summarized in Table 4.

Table 4. Simulated results of flatness error on the square box design.

| Parameter | ENG | DAS |
|---|-----|-----|
| Flatness of bottom surface [mm] | 1.0 | 0.8 |
| Flatness of lateral walls surface (long side) [mm] | 0.6 | 0.7 |
| Flatness of lateral walls surface (short side) [mm] | 0.3 | 0.3 |

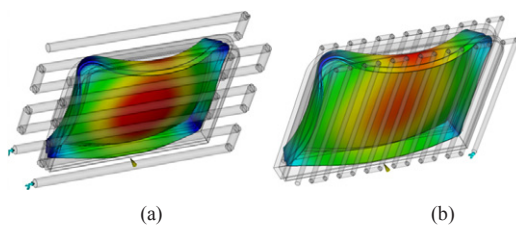


Figure 7. Comparison of product final shape (displacement magnification 25x and colour range from blue = -0.6 mm to red = +0.5 mm) of part moulded with: (a) ENG cooling design and (b) DAS cooling design.

4. Conclusion

A software engineering tool for the automated design of cooling systems on polymer injection moulds has been developed, established and its working principles

demonstrated. To validate the newly proposed design method, the cooling system layouts automatically produced by the design tool have been compared with solutions produced by a best-practice tool engineer. Verification of the new automated design tool as compared with engineering design solution was carried out by performing a series of injection moulding process simulations. The comparison was based on predicted part warpage. It was demonstrated that the automated design generation software can provide promising results for simple and prevalently planar geometries (i.e. square box), even though it is still challenged by more three-dimensional part (i.e. cylindrical part). To tackle this issue, the design tool is currently undergoing further development by:

- Introducing new pattern based rules derived from knowledge used by expert designers.
- Implementing Genetic Algorithms to drive the solution generation. The idea is to let GA identify combinations of absorber channels that maximizes the heat abortion of the cooling system while minimizing temperature differences in the part.

These modifications are expected to optimize the tool's performance and to extend the applicability of its design capability.

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